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A technical review of building-mounted wind power systems and a sample simulation model

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ABSTRACT

Small scale wind turbines installed within the built environment is classified as micro generation technology. This paper reports the investigation results of wind power application in buildings. First, general information is given for common type of wind turbines are used on buildings. Second, the wind aerodynamics and wind flows over the buildings are investigated based on local meteorological data and local building characteristics. However, to receive the highest potential wind energy resource and avoid turbulent areas, the tool of Computational Fluid Dynamics (CFD) has to be used to model the annual wind flows over buildings to help analyze, locate, and design wind turbines on and around buildings. Three different sample models for buildings and rural residential areas are explained with CFD models.

Contents

1. Introduction

Urban energy generation such as that produced by small scale wind turbines or photovoltaic systems installed on or around buildings can be defined as micro generation [1]. The term applied equally for the generation of energy – heat or electricity – by individual buildings or small groups of buildings. Such technologies also include micro-combined heat and power (CHP), solar thermal, photovoltaic, fuel cells and micro-hydro systems. In contrast to the traditional centralized energy supply, micro generation Technologies bring power generation close to the user to sustain their homes or buildings. It is estimated that there is a huge potential to utilize this type of technology in the urban built environment not only to satisfy demand and provide decentralized generation but also

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Nomenclature

μ_t	turbulent (or eddy) viscosity
ρ	fluid density
C_μ	constantfor the turbulence model
k	turbulence kinetic energy
ε	turbulence rate of dissipation
Z	boundary layer
Z_0	roughness height
d	zero plane displacement

to help tackle fuel poverty and achieve reductions in emissions. Smart use of energy should be implemented in buildings either at the initial stage of construction or at the time of renovation [2,3].

One of the approaches being used, and investigated more frequently, is the incorporation of power-generation, primarily solar and wind devices, into the design of the building. The requirements for optimizing the performance on wind generators in an urban environment are quite different from the considerations of the open sites that have traditionally been the domain of wind farms. Small wind turbines of any type inevitably have higher costs per unit of electricity produced than wind-farm machines, and so are unable at present to compete with conventional sources of energy. But the same may be said of photovoltaic systems, and these are finding widespread application in urban environments throughout the world. This requires the use of different design approaches to assess the most suitable generator types, develop building forms that will enhance their efficiency, and predict expected power outputs [4,5].

Since the majority of the world's population lives in urban areas, implementing micro generation for urban houses has the potential to make a significant contribution to renewable energy targets. Micro generation at the single-building scale using rooftop wind turbines is one technology being used on urban houses, increasingly in European cities [6]. Wind energy in buildings, with turbines being mounted on or integrated into buildings, involves many different challenges for stand-alone wind energy systems. Wind turbines located at the high wind speed zones in buildings are called Building Augmented Wind Turbines (BAWTs), and the wind turbine makes use of buildings as a concentrator of wind. So far, the existing utilization types in urban areas are: building mounted (small-scale wind turbines), including Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbines (VAWTs) [7].

Micro-wind turbines are classified in terms of their swept areas (<25 m^2) and therefore, have rated powers of up to 6 kW. Small micro-wind turbines (<0.5 kWp) have historically been used in the UK for off-grid battery charging applications, most notably on sailing boats. Over the last five years there has been an increasing interest in the application of micro-wind turbines for use on buildings. These turbines are either evolutions of off-grid products or specially designed for the built environment market. Some manufacturers claim improved performance for their devices at lower wind speeds, more representative of the urban environment and often rate the power of their turbines at wind speeds less than the 15 m/s associated with full scale MW devices [8].

Mertens [9] in his work presents a methodology to extrapolate a rural wind into an urban transition in terms of a step change which was further developed by Heath et al. [10] in which a CFD model was used to simulate the wind flow around a simple pitched roof building with regard to the potential energy yield of a micro wind turbines installed at optimal heights within an urban canopy. Watson et al. [11] synopsize the work by both Mertens and Heath, where based on an initial Wind Atlas means wind speed and in conjunction with CFD analysis with respect to local building geometries, the temporarily and spatially averaged wind profile was investigated. From this investigation, the Weibull wind speed distribution was used to calculate micro wind turbine yield and capacity factor [12].

Safe and reliable deployment of wind turbines in the highly turbulent built environment is specialized and technically challenging. In almost all situations the use of existing (small) wind turbines will be problematic due to the fact that they are not adapted to the complex wind environment and to additional building related requirements. Some of these requirements are the severe noise restrictions and the ability to match the structural and esthetical integrity of buildings. This means that new ways need be found in the design of new wind turbines that do fit the requirements for the built environment. Non-technical barriers such as economics, bureaucratic and regulatory issues will not be addressed, although they are very important for successful implementation of wind turbines in the built environment [13].

This paper reports the investigation results of wind power application in buildings in a five sections. At Section 1, domestic electricity demands explained for the home accounts both workdays and weekends. And Section 2 general information is given for common types of wind turbine are used on buildings. Micro-wind turbines are commonly used for building mounted systems is examined briefly at Section 4. Finally, the wind aerodynamics and wind flows over the buildings are investigated based on local meteorological data and local building characteristics at the last section. The tool of Computational Fluid Dynamics (CFD) has to be used to model the annual wind flows over buildings to help analyze, locate, and design wind turbines on and around buildings. Three different sample models for buildings and rural residential areas are explained with CFD models.

2. Domestic electricity demand

Energy use in the home accounts for significant proportions of total energy-consumption both in industrialized and developing countries. The operation of most types of domestic appliance, lighting and air conditioning relies upon electricity and these results in substantial carbon dioxide emissions per household [14].

Forecasting or predicting domestic electricity demand on an hourly basis is very difficult unless a great deal is known about the dwelling, such as the number of occupants, age, lifestyle habits and the quantity and nature of electrical devices. Even with all this information there are other factors that serve to make predicting electricity demand a very uncertain process [2].

These may include irregular routines, occasional working from home, holidays and over occupancy due to visitors. However, despite all these factors it is possible to see general trends in demand. There are the typical weekday patterns of high morning and evening demand as people arise, go to work and return in the early evening [2].

Weekends tend to have a higher daily demand as people stay in during the day more especially during the winter months. Such a pattern is applicable for example, to families with children. It follows that other behavioral trends exist for differing lifestyle groups such as shift workers, the retired or a mother at home with a young family. The base load will depend upon the number and nature of consumer appliances in the dwelling and will gradually increase over time as more are added and efficiencies of certain devices (such as freezers) degrade [2].

Fig. 1 is shown the domestic consumption of electricity in Turkey and observed change in electricity consumption on weekdays and weekends.

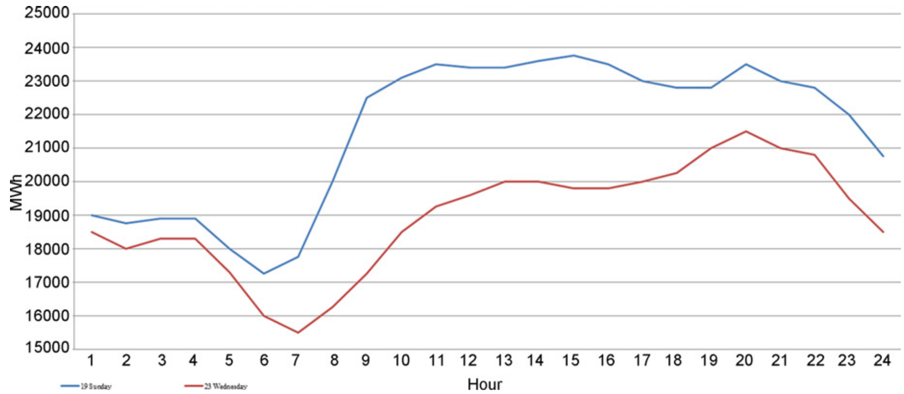


Fig. 1. Weekday and weekend load consumption curves in September 2007 in the Turkey [15].

3. Common types of wind turbine for buildings

There are three basic types of wind turbine in common use today: the horizontal axial propeller, and the vertical axial Darrieus and Savonius turbines.

3.1. Horizontal axial wind turbine

The horizontal-axis wind turbine (HAWT) is the most frequently used type found in operation (Fig. 2). Whilst being geometrically simple, its operating regime is aerodynamically complex and, in some cases, particularly unsteadies [16].

3.2. Vertical axial Darrieus

The Darrieus-type VAWTs are basically lift force driven wind turbines. The turbine consists of two or more aerofoil-shaped blades (Fig. 3) which are attached to a rotating vertical shaft. The wind blowing over the aerofoil contours of the blade creates aerodynamic lift and actually pulls the blades along. [17].

3.3. Vertical axial Savonius

The Savonius rotor is a Vertical Axis Wind Turbine (VAWT) invented in 1924 by the Finnish engineer Sigurd Savonius. It consists of two half cylinders staggered along their common diameter (Fig. 4). The interest of the Savonius rotor is that, it functions in wind speeds as low as 1 m/s and it possesses a very high starting torque. In addition, it is rustic and little technology required in constructing it compared to the HAWT [18].

4. Micro-wind turbine energy analysis

Micro-wind turbines need to be affordable, reliable and almost maintenance free for the average person to consider installing one. This often means a sacrifice of optimal performance for simplicity in design and operation. Thus, rather than using the generator as a motor to start and accelerate the rotor when the wind is strong enough to begin producing power, small wind turbines rely solely on the torque produced by the wind acting on the blades. Furthermore, small wind turbines are often located where the generated power is required, and not necessarily where the wind resource is best.



Fig. 2. Bergey Excel horizontal axis 3-bladed propeller wind turbine.



Fig. 3. Turby vertical axis twisted H-Darrieus wind turbine.



Fig. 4. Savonius turbine.

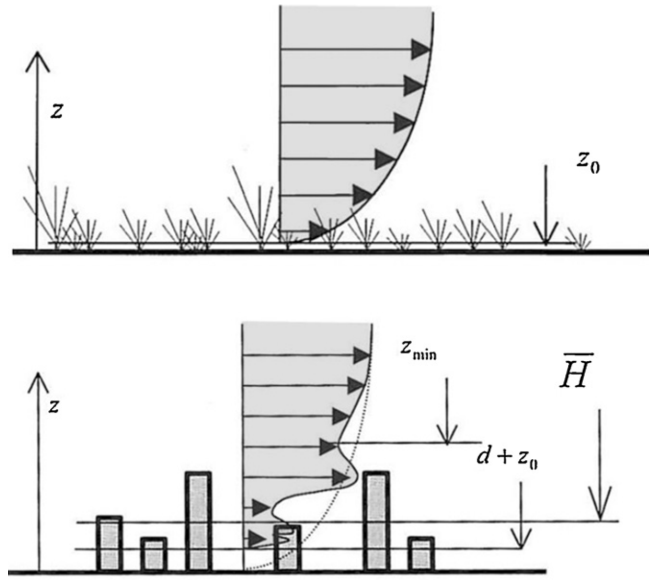


Fig. 5. Diagrammatic approximations of wind velocity profiles in open field (a) and urban settings (b) [21].

In these low or unsteady wind conditions slow starting reduces the total energy generated. Also, a stationary wind turbine fuels the perception of wind energy as an unreliable energy source [19].

Wind conditions in urban environments tend to be very different. The effect of urban environments on a boundary-layer is shown in Fig. 5. This shows how buildings slow the wind near to the ground, and increase the turbulence in the wind.

Turbines work most efficiently in low-turbulence environments so care needs to be taken in specifying turbine types that will cope with both existing turbulence and likely future changes in turbulence as a result of urban development [4,20,21].

Generally, it is desirable to locate turbines in regions of high wind speed and low turbulence. Describing the wind flow around a tall buildings can be quite complex and has been studied in depth for many years (Cermak, 1971, 1975 and 1976). A simplified sketched of the mean flow phenomenon is shown in Fig. 6. There will be positive pressure on the windward face and negative pressure on the side and leeward faces. As air, or any fluid, will naturally flow from areas of high pressure to low pressure this implies that the most effective locations for wind turbines will be either in the accelerated shear layers around the edge and top of the building or in specially developed passages linking the areas of positive and negative pressure. Note that wind speeds close to the center of the roof may be low as this area is often in a region of separated flow [4,22].

In order to assess the suitability of micro-wind electrical energy generation in the built environment the modeling tool m-wind was developed. m-Wind is composed of four modules [2].

- Wind resource.
- Turbine performance.
- Electricity demand data.
- Financial and carbon savings analysis.

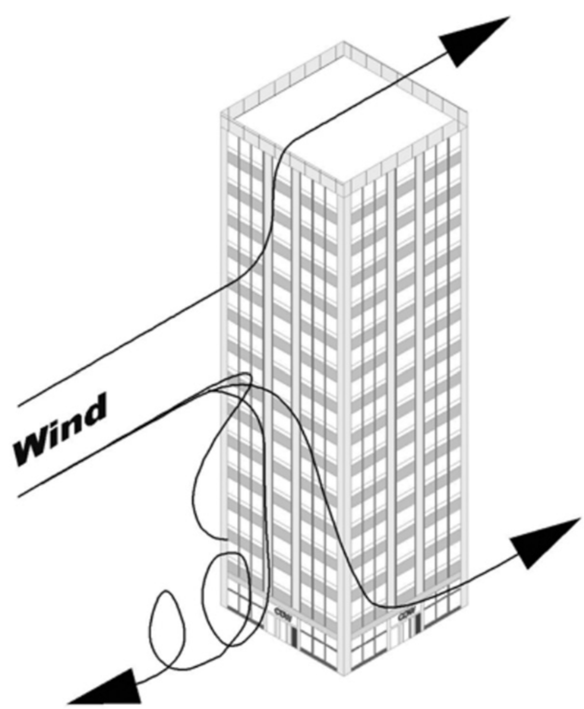


Fig. 6. Wind flow around a tall building [23].

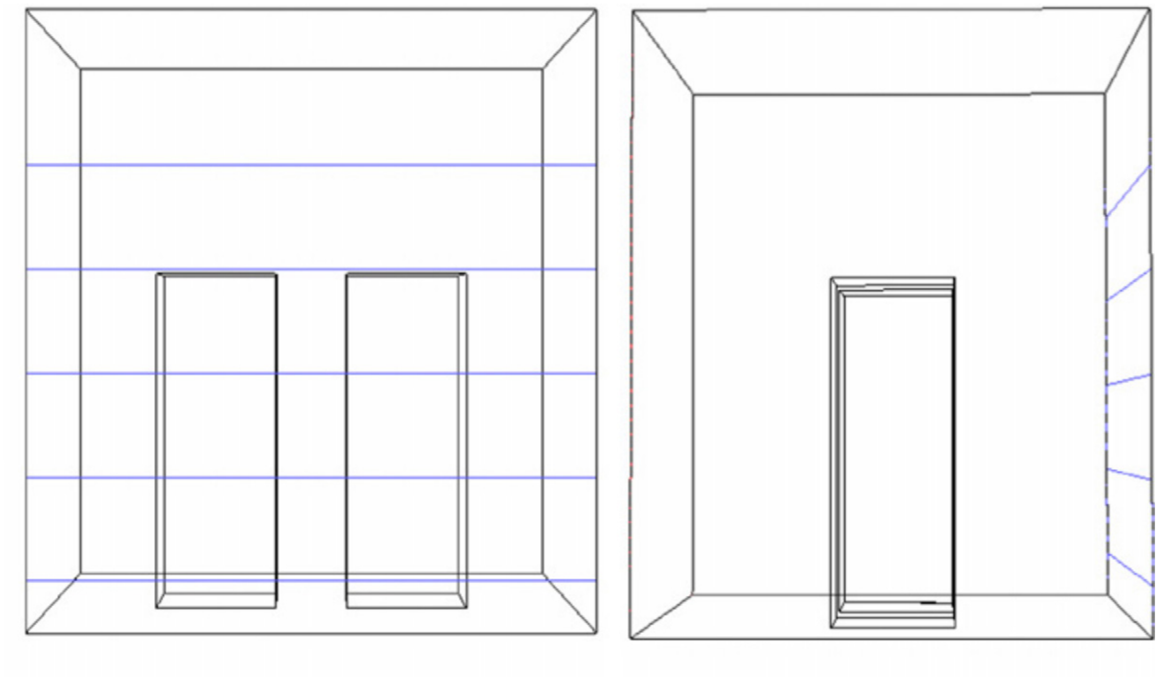


Fig. 7. Case 2 (building distance: 15 m) [7].

5. Feasibility and enhancement methods of wind power for building-mounted systems

5.1. Computational Fluid Dynamics (CFD)

Computational wind engineering (CWE) has been developed recently to evaluate the interaction between wind and buildings numerically, and Computational Fluid Dynamics (CFD) can be used to model wind flows over buildings to help analyze and locate turbines in and around buildings. Domestic wind turbines are designed to be mounted close to the building.

Most manufacturers suggest a maximum mast length of 3 m. This implies that the wind flow will be strongly influenced by the building. CFD modeling is used here to determine the effects of the building at points where a turbine might be mounted [7,9].

Several previous studies have used CFD methods to model wind flow around buildings [9,10,24]. A number of different techniques have been employed in CFD simulations including: Direct Numerical Simulation (DNS) [25]; Large Eddy Simulation (LES) [26], or the Reynolds-Averaged NaviereStokes (RANS) method with various turbulence models [27].

The choice is generally made based on the details of the flow to be obtained and the computing resources available [27].

5.1.1. Mathematical modeling

Turbulence modeling and meshing are the two major issues considered to be important for successful application of Computational Fluid Dynamics to environmental flows. The FLUENT provides several turbulence models, and the standard k–e model [7,28] is applied. The turbulence kinetic energy, k, and its rate of dissipation, ε, are obtained from the following transport equations:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (1)$$

5.1.2. Geometry scenarios and building layout

Based on local building characteristics, three scenarios are chosen to investigate the wind conditions between two buildings in terms of building heights and the distances, and to study the wind flows over the building roof considering shapes and building heights.

5.1.2.1. Wind flows between buildings with different building distances. Scenario [7] is to find out the effect of different building distances on the wind flows between buildings. Three cases are simulated with the distances of 10 m (Case 1), 15 m (Case 2, see Fig. 7) and 20 m (Case 3), respectively. The dimension of the two identical buildings is 25 m × 70 m (h) × 25 m.

Increase of wind velocity and wind power density between buildings The wind velocity in the vertical channel of two buildings increases sharply from the inlet boundary, reaches the highest at the narrowest point of the two buildings and then decreases to the outflow boundary (see Fig. 8). The highest wind speed exists at the middle level of the building height, and there is also wind increase near the side walls of the buildings [7,29].

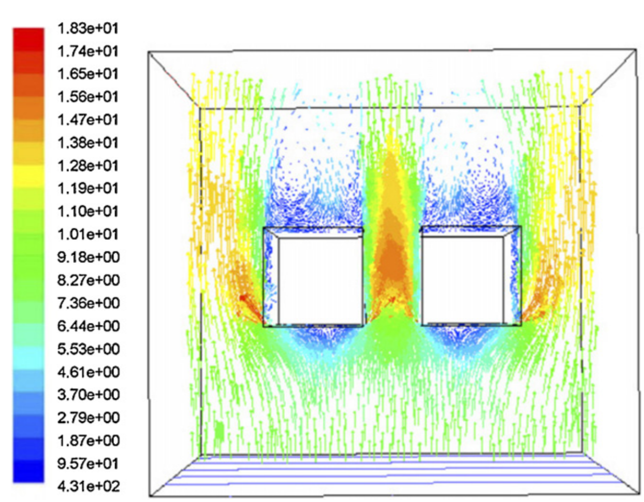


Fig. 8. Contours of velocity magnitude (m/s) of: Case 2: top view [7].

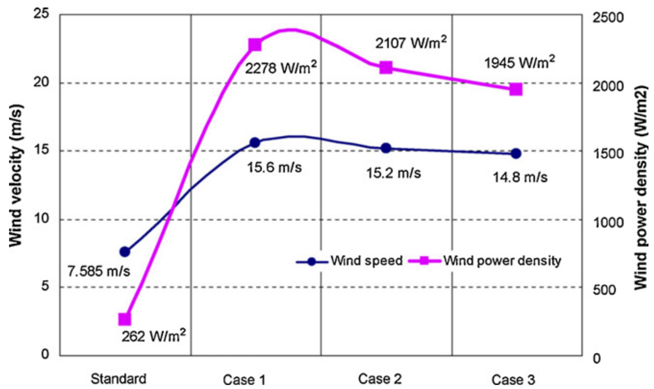


Fig. 9. Comparisons between the standard input and the highest wind speed &wind power density in scenario [7].

For the three cases, under the given simulation conditions, the highest wind velocity between buildings could reach around 15 m/s, which means around 8× increase of wind power density due to the cubic relationship between wind speed and wind power density, as demonstrated in Fig. 9. The power density over 2000 W/m^2 is much higher than the standards of the highest wind power class of 7 (>800 W/m^2 at 50 m high) defined by DOE.

The results prove that the concentration effect between buildings can increase wind power generation significantly. Although the integration of large-scale wind turbines is far too expensive to put into practice at the moment, the yields of the wind turbines could be increased by a few times once optimal location is selected, which will offset the high initial cost [7,29].

Amongst three cases, Case 1 has the highest velocity of 15.6 m/s due to the shortest building distance. The distances between buildings affect the increase of the wind speeds, and theoretically, higher wind velocity exists with shorter building distance. However, other considerations need to be taken as well, such as building design standards, the dimension of wind turbines, and the layer thickness of turbulent flows [7,29].

5.1.2.2. Wind flows over two buildings of different heights. To investigate the wind flow patterns between two buildings with different

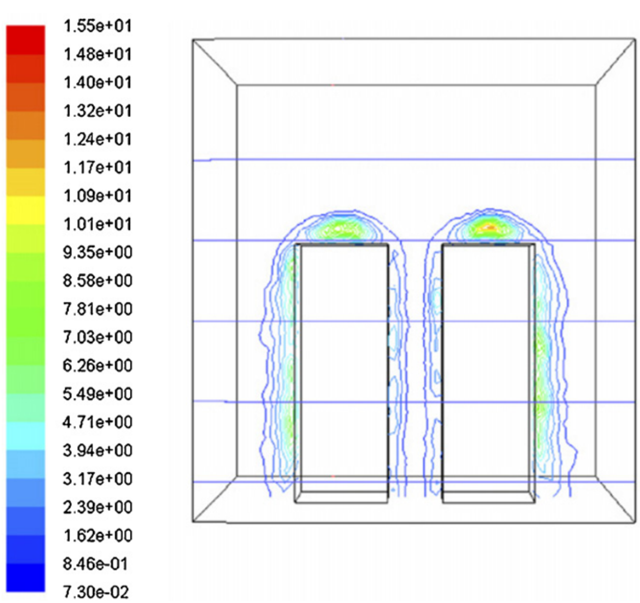


Fig. 10. Contours of turbulence magnitude (m^2/s^2) of scenario: Case 2 (front view) [7].

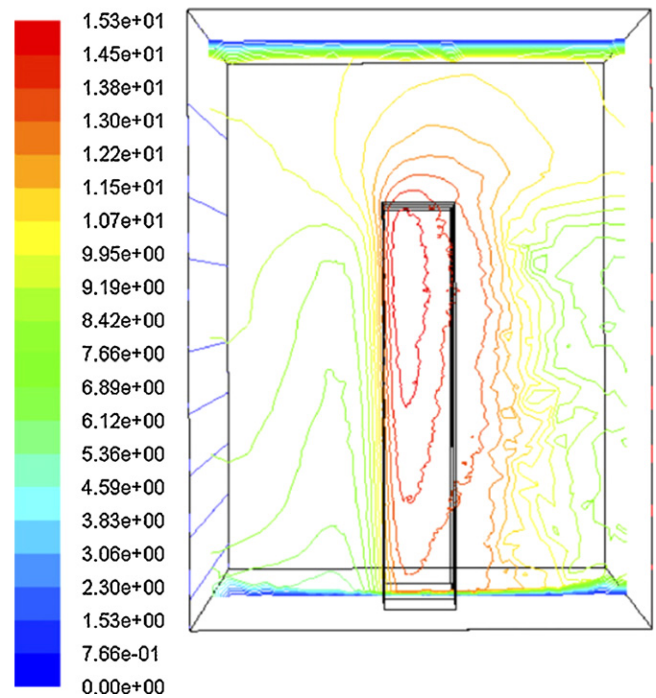


Fig. 11. Contours of velocity magnitude (m/s) of scenario: Case 2 (side view) [7].

heights, scenario [7] with two cases of building heights of 70 m (Case 1) and 140 m (Case 2) are studied, as shown in Fig. 10.

The wind flow patterns are similar for the two cases, and the highest wind speeds are both around 15.2 m/s (see Fig. 11). However, the occurrence positions of the highest speed are different for the two cases. The occurrence of the highest velocity for Case 1 starts relatively lower from 17 m (1/4 of the building height of 70 m) above the ground to 70 m, and for Case 2 relatively higher from 70 m (1/2 of the building height of 140 m) above the ground to the building height.

It concludes that the building heights have little effects on the wind speed increase between high-rise buildings, but affect the favorite position level for wind energy utilization between high-rise buildings. For the wind flows between two buildings, the building heights affect the occurrence positions of the highest wind velocity. For tall buildings, the position favorable for wind power utilization is relatively higher [7,29].

5.1.2.3. Wind flows over the roof. Three buildings are chosen with the height of 70 m for Building 1 (the left one), 140 m for Building 2 (the middle one) and 210 m for Building 3 (the right one). Wind flows from the left inlet boundary to the right outflow boundary.

Obviously, higher wind speeds exist over the tallest building. Fig. 12 demonstrates that the wind speeds (from 9.51 to 12.7 m/s) over the roof of Building 3 are much higher than those of Building 1 and Building 2.

There are two reasons for the increase: the wind speed increase with the height, and the concentration effect of the buildings. The patterns of wind flows over different flat roofs are similar. Meanwhile, the roof of the taller building is suitable for wind power utilization if the construction design allows.

In this case, the wind speed could increase by around 2× (compared with the ground wind speed) and almost 1.5× (compared with the wind speed at same height in open area), which means 8× or 3–4× higher of wind power generation yield theoretically. Thus, using wind power effectively in buildings could be feasible and economical in terms of the investigation [7,29].

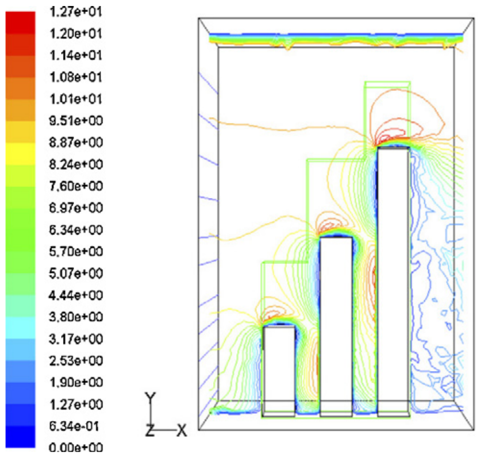


Fig. 12. Contours of velocity magnitude (m/s) of scenario [7].

5.1.2.4. Building layout. Every building is different and the wind flow around it is affected by many factors, from its shape and size to the positioning of chimneys and dormer windows. Only a very simple building has been modeled here, but it is enough to demonstrate certain effects.

The model, shown in Fig. 13, is of a simple pitched-roof house. It is 10 m (i) × 10 m (j) × 10 m (H), with a 45° pitched roof. This is roughly the equivalent of a two-story building [10,30].

The semi-log wind profile described above is intended to represent the wind flowing through an urban area. However, it is a spatial average and should not be used to predict the instantaneous wind speed at a given point. Therefore, it is not adequate to simply model a single building with this profile for the inflow wind. Neighboring buildings must be included in the model.

A simplified version of a suburban neighborhood has been modeled here, with houses arranged in a staggered array in a street-like manner, as shown in Fig. 14. Ground in between buildings was modeled with a surface roughness length of 0.001 m, appropriate for a surface such as well-mown grass, concrete or tarmacs [10,30].

Fig. 15 shows the adjustment of a westerly wind as it flows through the building array. There is a general decrease in velocity as the wind crosses the rows of houses. This suggests that the inflow wind profile has not been calculated correctly. If it were, the spatial mean wind velocity should not change as it moves through the array. This is not surprising, as the profile was calculated assuming a regular array of cubes. In addition, the first row of houses may be affecting the inflow profile to some degree [10,30].

The rest of the results presented here will concentrate on wind flow around the building in the middle of the most downwind row

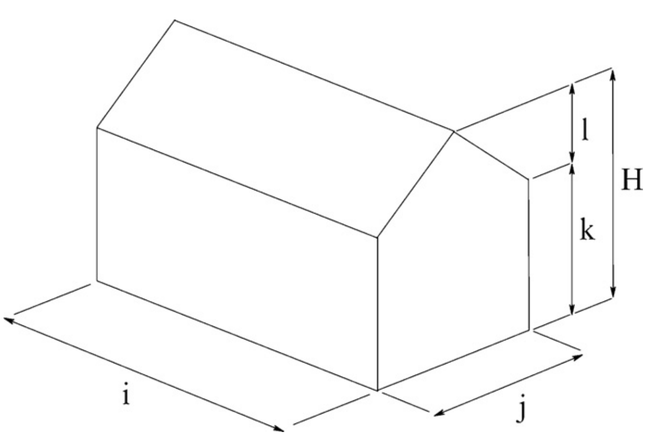


Fig. 13. The ‘typical’ two-story house used in the CFD wind flow modeling [30].

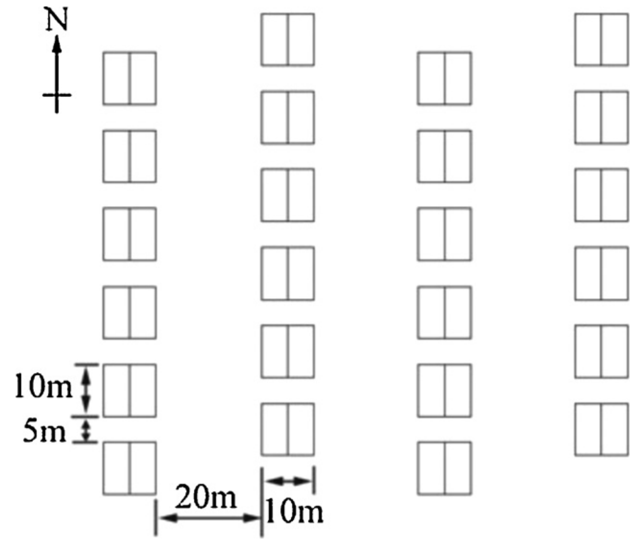


Fig. 14. The building arrangement used to simulate streets of houses with the CFD model [10].

of houses. Exactly which building this is will vary depending on the wind direction?

Fig. 16 shows the flow of a westerly wind across the house. It can be seen that the velocity is generally much lower than upstream of the buildings. Below roof height, the velocity is very low, and there is a large, slow area of re-circulation downstream of the house. Higher up, the velocity decreases as the wind approaches the house. It increases very slightly as it crosses the ridge and then slows again [10,30].

5.2. Assembly forms to the building of wind turbines

Building-mounted turbines, using one of the generic options shown in Fig. 17, will generally be very difficult unless very small

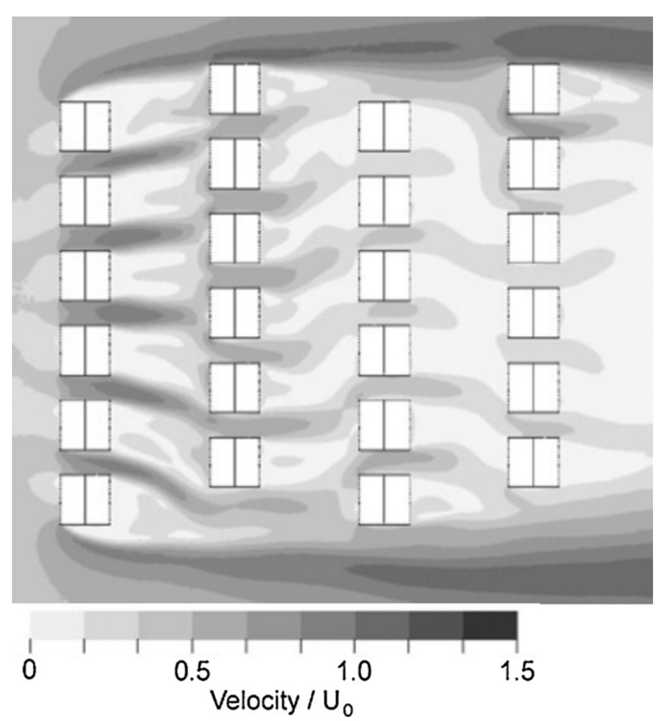


Fig. 15. Normalized magnitude of the wind speed at z/H = 0.5 within the building array for a westerly wind [10].

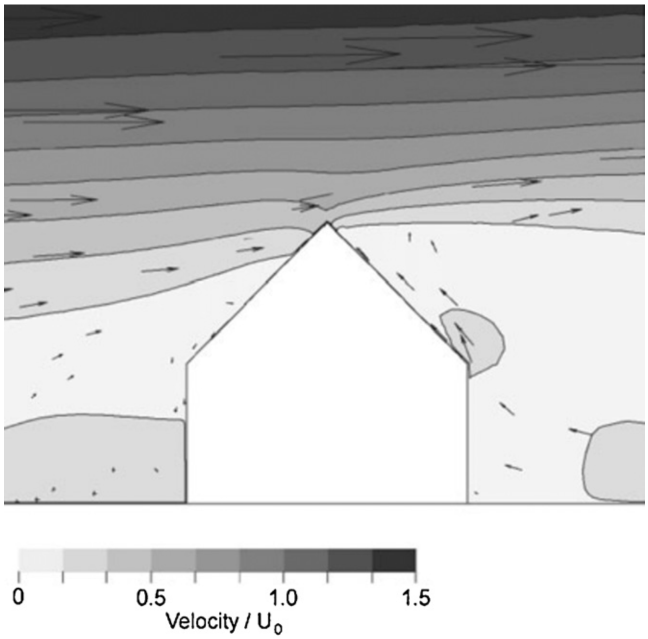


Fig. 16. Wind velocity profile across a house in the middle of the most downwind row of houses within the building array [10].

turbines (generally contributing an insubstantial fraction of the building's electricity demand) with small impacts on the building and surroundings are considered [31].

5.2.1. On top of building mounted turbine

There are some horizontal (Fig. 18) and vertical (Fig. 19) wind turbine applications top of the building.

HAWTs are sensitive to the changes in wind direction and turbulence which have a negative effect on performance due to the required repositioning of the turbine into the wind flow. The best locations for HAWTs are open areas with smooth air flow and few obstacles [32].

Vertical Axis Wind Turbines (VAWTs) are typically developed only for the urban deployment (Fig. 19). Changes in wind direction have fewer negative effects on this type of turbine because it does not need to be positioned into the wind direction. However, the overall efficiency of these turbines in producing electricity is lower than HAWTs [32].

5.2.2. Beside of building mounted turbine

Beside of building mounted turbines usually prefer to HAWTs (Fig. 20). VAWTs aerodynamic structure is not suitable to this form.



Fig. 19. View of rooftop installation of VAWT (windterra Eco 1200) [34].



Fig. 18. Rooftop HAWT turbine (1.4 kW high output) [33].

The sites with best performance were always remote rural locations, usually individual dwellings near the coast or on exposed high land such as moors. The turbines performed best when mounted on the gable end of a building and positioned above the ridge line [8].

5.2.3. Between two building mounted turbine

Wind flow velocity between two buildings is increasing. Using it the flow of wind between two buildings moves to turbine blades. The HAWT and the VAWT turbines both can be used for enhancing performance between two building mounted turbines (Fig. 21). Power enhancement (accounting for conversion losses) for both turbines is improved by a large ratio at low wind speeds (where the stand-alone turbine would be producing minimal power) and appears to reach a lower ratio at high wind speeds. The performance of the HAWT in the prototype

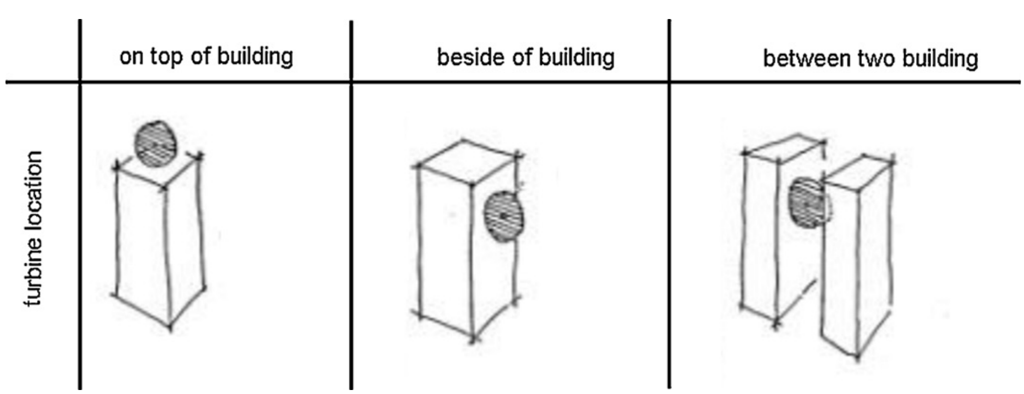


Fig. 17. Generic options for mounting a wind turbine to a building [31].



Fig. 20. Ampair 600 230 wind turbine mounted on the gable end.



Fig. 21. Photographs of the prototype aerodynamic building [31].

without infill's is improved by a factor of between 1.2 and 1.3 (depending on incident wind angle) at 8 m/s, and the VAWT by a larger factor (probably due to its particular characteristics) [31].

6. Conclusions

This paper reports an investigation result of the feasibility of wind power utilization in local urban areas and find out how to develop wind power in the built environment more effectively. By investigating the wind aerodynamics and wind flows over the buildings based on local meteorological data and local building characteristics, the concentration effect of buildings and the heights of buildings could enhance wind power utilization by increasing the wind power density by 3–8× under the given simulation conditions. Computational Fluid Dynamics (CFD) should be used to model annual wind flows over buildings to help analyze, locate, and design turbines in and around buildings for both receiving higher wind speed and avoiding the turbulence layer. For different wind conditions and different dimensions of roof with different building heights, the thickness of turbulence layer and the changing of wind speed could be different, and annual dynamic simulation investigations should be conducted for the specific application [7,29].

When assessing the merit of building-mounted wind turbines, it is important to consider that wind conditions near the building surface will be very different from the general wind conditions in the region, due both the influence of neighboring structures and the effects of the building itself. The winds will typically be gustier, hence uneven across the turbine blades, which can significantly affect the turbine performance. A range of tools are available to assess both the turbine performance and the local wind environment, including wind tunnel simulations, computer simulations, and full scale testing.

Different mounting positions are better suited to different prevailing wind situations. It is worth noting that the very center of the roof rarely outperforms other mounting positions. The increased difficulty of mounting a turbine here means that it can normally be ruled out as a potential mounting point. The wind is very strongly sheared at rooftop height. This makes the height of the turbine mounting extremely important. If domestic turbines are to produce optimum yield, local authorities must grant planning permission for turbines to be mounted above the rooftop ridge line [10,30].

In this study shows that for such urban locations much smaller Vertical Axis Wind Turbines provide good solution. The standard Darrieus wind turbine is not very well suited, since it is too noisy. A Savonius rotor has the disadvantage of a fairly low power coefficient. By modification of the original Darrieus design, a.o. by reducing the design tip speed ratio (TSR) and by applying blade sweep, noise production can be minimized. Thus new concepts have evolved which are much better equipped for application on (existing) buildings. Typical dimensions are around 10–20% of the characteristic building height.

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